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Predicting Water Quality in Distribution Systems

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16. ABSTRACT

The quality of a public water supply although acceptable when it leaves the treatment plant, may deteriorate before it reaches the user. Deterioration may be caused by either chemical or biological transformations or by a loss of system integrity. There have been a growing number of coliform regrowth and biofilm formation situations reported in distribution systems.

A water quality prediction model has been developed in cooperation with the North Penn Water Authority. This cooperative agreement has focused on the hydraulic behavior of the system, examination of historical water quality sampling data, and steady-state modeling of water quality within the distribution system. The steady-state model has been developed and field tested. A dynamic model is under development. The results of this work suggest that the dynamic features, of system behavior, such as variations in water quality, changes in demand and mixing of water from different sources, will be significant in predicting water quality in distribution system.

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INTRODUCTION

The quality of a public water supply although acceptable when it leaves the treatment plant, may deteriorate before it reaches the user. Deterioration may be caused by either chemical or biological transformations or by a loss of system integrity. There have been a growing number of coliform regrowth and biofilm formation situations reported in distribution systems.

Mechanisms that may cause this deterioration include chemical and biological transformations, or loss of system integrity. Organics and other nutrients may enter into the water distribution network with the raw water, may be produced during treatment or enter through leaks, or cross connections. Growth or regrowth may be observed in distribution systems despite treatment and disinfection at the treatment plant which is intended to eliminate such microbial activity.[1] Microbiological growth may occur in the network, in the water or on the walls in the form of biofilms. Bio-cells may be trapped in mineral deposits known as tubercles. Growth occurs at the expense of the nutrients in the water and if disinfectant residuals cannot be maintained throughout the entire distribution system the potential for growth in pipe networks is greatly enhanced.

In addition to the microbiological degradation that may take place in the water in distribution systems, there is the problem of chemical deterioration as well. For example, corrosion byproducts may occur when material is leached from the walls of pipes. High concentrations of lead may occur in household plumbing systems if aggressive water is distributed to the customer. Figure 1 illustrates some of these deterioration mechanisms. Figure 2 is a more detailed illustration of the interactions that take place at the pipe wall interface.

Table 1 contains a list of municipalities that reported coliform regrowth situations in the United States. Table 1 illustrates the concern over maintenance of water quality in distribution systems as delivered to the customer.[2] In response to this concern EPA's Drinking Water Research Division has sponsored a series of projects that deal with

distribution system problems. This paper will briefly review EPA's distribution system research. Research into the development of models for predicting water quality variations in systems will be discussed in some detail.

A water quality prediction model has been developed in cooperation with the North Penn Water Authority. This cooperative agreement has focused on the hydraulic behavior of the system, examination of historical water quality sampling data, and steady-state modeling of water quality within the distribution system. The steady-state model has been developed and field tested. A dynamic model is under development. The results of this work suggest that the dynamic features, of system behavior, such as variations in water quality, changes in demand and mixing of water from different sources, will be significant in predicting water quality in distribution system.

EPA's DISTRIBUTION SYSTEM RESEARCH

EPA's research in distribution system problems may be classified into three major categories: microbiological studies; corrosion studies; and, infrastructure/system studies. Microbiological studies have focused on developing new techniques for recovering and identifying organisms. Research is being conducted into: development of the concept of assimilable organic carbon; examination of stressed organisms; understanding the mechanisms and causes of biofilm formation; identifying and classifying tubercles; and, investigating and understanding problems related to coliform regrowth studies. Studies have been conducted to determine the extent of lead leaching from household plumbing and into factors effecting deterioration of asbestos cement pipe. Work has also been conducted on development of corrosion indicators and chemical corrosion kinetics. In the infrastructure/system area, a microcomputer system for maintaining break and leak complaints records has been developed.[3,4] Statistical measures for assessing the probability of breaks and leaks occurring in networks are being developed and attempts are being made to determine the physical factors causing breaks and leaks. Research is being conducted to acquire an understanding of the hydraulic conditions that affect biofilm formation. Techniques for predicting water quality in distribution systems are being developed.

MODELING RESEARCH

Distribution system modeling is very complex. Variations in system flow occur because of the way in which the system has been designed. Hydraulic analysis and verification of flows in a system is an art in itself. Predicting demand is also an art. Demand variations complicate the problem of predicting and modeling flows in distribution systems. Hydraulic and demand variations, the mixing of water from different sources, and the kinetics of formation of biological and chemical products all make the modeling of water quality in distribution systems a complex and difficult process. Two approaches to predicting water quality in distribution systems are described in this paper. One approach is based on a steady state modeling concept and has been verified by field evaluation.[5] The other is a dynamic modeling approach for which an algorithm has been developed and which will be described in this paper. The North Penn Water Authority north of Philadelphia, PA. was used as a test case for this research.

THE NORTH PENN SYSTEM

The North Penn Water Authority has an average production of 5 million gallons a day, and consists of ten municipalities with 225 miles of pipe. It serves over 14,500 customers and has three pressure zones plus several small satellite systems. Its water sources include purchased treated water which amounts to about one million gallons per day of supply plus 40 individual wells. There is wide variation in water quality from these different sources. Figure 3 shows a schematic of the North Penn Water Authority distribution system. The Keystone tie-in is the surface water source coming into North Penn from the south. The various wells in the Lansdale low pressure zone, Lansdale high pressure zone and Souderton high pressure zones are shown. Pressure zone boundaries are shown as dotted lines and storage tanks are shown by inverted triangles. Compliance or routine sampling points used for monitoring are designated by "x".

In order to perform the hydraulic analysis a link and node representation of the network was used. Beginnings of pipes, junction of pipes as well as tanks are represented as nodes and the pipes themselves are represented as links. Hydraulic models were used to determine flows in the links.[6,7] In the steady state analysis it is assumed that consumer demands and tank flows and heads are constant. The resulting steady state or equilibrium flows and velocities throughout the system are then determined. In dynamic or quasidynamic modeling, demands, inflows, and tank heads, are fixed for a time period and the steady state solution calculated. During the next period, tank conditions are calculated based on flows and tank elevation in the previous period. New demands and inflow conditions in the next period are used to determine a new steady state solution. In the true dynamic solution, there is transient behavior in the system. The water in the system travels in a wave at a speed much greater than the actual flow, but for all practical applications the quasi-dynamic solution is acceptable.

STEADY STATE SOLUTION

In order to determine and predict the steady state concentrations of contaminants in the distribution system, a steady state hydraulic solution was used along with the known concentrations in the water sources to determine the resulting steady state spatial distribution of concentrations throughout the network. The approach used was to formulate a mass balance around each node and solve for the resulting concentrations.[8,9] The development of the equations at a node is illustrated for the specific case shown in Fig. 4, in which two pipes deliver water to node i, and there is a single discharge link delivering water to node x.

The flow directions and quantities are known because it is assumed that the network has previously been solved hydraulically. We can define Q_{ij} as the flow into node i from node j. Q_{ij} is thus equal to $-Q_{ji}$. We consider the unknown concentrations of the constituent of interest at nodes i, j and k, to be C_i, C_j and C_k, respectively. The known volume of flow from an external source delivering water to node i is S_i, and the known constituent concentration in the external source is SC_i. For the sake of simplification of notation, the total influent water from all sources to node i is defined as I_i, and in the case shown in Fig. 4, this quantity = $S_i + Q_{ik} + Q_{ij}$.

By mass balance for flow at node i, the flow leaving node i for node x, Q_{xi}, is given as follows:

$$Q_{xi} = S_i + Q_{ij} \qquad (1)$$

By mass balance for the constituent itself, assuming complete mixing at node i:

$$C_i = \frac{[(Q_{ik}*C_k) + (Q_{ij}*C_j) + (S_i*SC_i)]}{I_i} \qquad (2)$$

Eq. 2 states that the average concentration at node i of the constituent of interest is equal to the total mass of the constituent delivered per unit time from all influent sources to node i, divided by the total quantity of influent flow at node i. By definition then, the concentration in link xi = C_i.

For the complete network, the flows and flow directions are known by a previous solution of the hydraulic network, and all Q_{ab} and I_a are known for all nodes a and b. Assuming n nodes in the network, we have n equations of the general form of Eq. 2 (with one C*Q product contributed for each link influent to the node), and n unknowns, the C_i at each of the n nodes. The external source quantities and concentrations are known as boundary conditions for each of the nodes at which water enters the network from an external source. The equations are linear in the unknown concentrations, and can readily be solved by standard methods. As with the case of the hydraulic analysis of networks, the coefficient matrix thus developed is sparse, and can profitably take advantage of sparse-matrix simultaneous equation solution techniques.

This concept has been discussed elsewhere and is called the SOLVER algorithm. In the steady state solution the SOLVER algorithm was applied to the main pressure zone of the system which represents 75 percent of the system demand. A hydraulic scenario considered to be representative of "average" conditions was selected. Wells are assumed to be on and water is flowing into the evaluated Chestnut Street and Lawn Avenue tanks. Model predictions were made of concentrations associated with Keystone water throughout the Lansdale low pressure zone. Trihalomethane concentrations were used as a tracer in the system because of the surface water from the Keystone tie-in.[5] There are no triahalomethanes formed in the groundwater, and it was assumed that the triahalomethanes from surface water represented a relatively steady state concentration having exhausted the triahalomethane formation potential. The SOLVER algorithim was applied to North Penn for average TTHMs (47 micrograms per liter).

Figure 5 represents information gathered from routine TTHM surveillance information at North Penn for the date 4/16/84. Figure 6 represents the TTHM data for 4/16/85 and Figure 7 represents the average TTHMs concentration using surveillance data collected over a two year period. One can see the rather gradual decline from 45 micrograms per liter at Keystone to below 10 or 20 in the eastern, western and northern parts of the system. Figure 8 represents the steady state modeling predictions for the THMs. An examination of Figure 8 (as compared to Figure 7) shows that under steady-state conditions the model under-predicts the observed TTHM values to the north and west (near Lawn Avenue and

Harleysville respectively), but provides a more reasonable estimate of observed values in the central, eastern, and southern areas of the Lawnsdale pressure zone. However steady state solutions are unrealistic and limiting, therefore, a dynamic algorithm for predicting water quality has been developed.

DYNAMIC MODELING

Under dynamic conditions system demands and supplies are variable and there are temporal and spatial variations in quality. In order to investigate the nature of water quality variability within the system, an intensive sampling system program was conducted at six sites. Figure 9 shows the various sampling points used in the field study and Figure 10 depicts the results of the intensive sampling program using total trihalomethanes (TTHMs) as a tracer. One can see that there is quite a bit of variation at a given point within the 30 hour period, and that there is also quite a bit of variation within the system itself. Hardness is representative of the well water and is shown in Figure 11. At the Mainland sampling point a flushing back and forth of water between the surface source to the well source can be seen. The peaks of the TTHMs at Mainland are approximately 6 hours out of phase with the peaks from the wells indicating that water flow at this point is affected by the surface and ground water sources.

This analysis points out the problems in attempting to predict a dynamic situation using a steady-state mode. The average TTHM data represent long-term averages, of data taken over a number of years, at different times of the day. The pattern of flow in the NPWA distribution system varies during the course of a day, as wells cycle off and on. Late at night, when most wells are off, Keystone water is the primary source of supply for the Lansdale low pressure zone system, and this water passes into the western and northern portions of the system, where it can enter the Lawn Avenue tank. During times of the day when Lawn Avenue tank water enters the Lansdale low system, this water can be expected to have non-zero TTHM (due to the origin of at least a portion of this water from Keystone when Lawn Avenue is filling). The pilot sampling run of November 14-15, 1985 shows a range during the sample period from a maximum TTHM value of 36 ug/L to a minimum of 13 ug/L, at the inlet to Lawn Avenue. This range is consistent with the historical data of Figure 7, where a value of 18.8 ug/L is shown in the neighborhood of Lawn Avenue. Examination of the daily THM historical data of Figures 5 and 6 also shows elevation of TTHM towards Lawn Avenue, and higher values in the Souderton pressure zone, in the region of 12-16 ug/L, presumably from Lawn Avenue water pumped into the Souderton zone. Data from the pilot sampling run, taken at the Mainland sampling site, shown on Figure 10, shows TTHM values in the range from 9 to 34 ug/L, with significant variation. As concluded by the analysis of the pilot sampling run, Mainland has water from the wells in Harleysville (NP14, NP31, NP11, NP20, NP26, NP48) during the times of day when they are pumping, and from Keystone in the early morning hours. Historical data shows levels of TTHM of 2 to 6 ug/L in this area, as compared to the model prediction (with wells on) of 0 ug/L. The model does show, however, that the zone of blending of Keystone and well water is fairly close to Mainland, and thus, simply from an examination of the model prediction, Mainland would be expected to show the variations that it in fact does show. (The Mainland site was selected primarily to test this hypothesis in the pilot sampling run).

While the initial steady-state modeling did provide useful information, in particular insofar as design of the pilot sampling study was concerned, it was obvious that the attempt to model the dynamic nature of the complex NPWA system with a single steady-state predictive model run, proved inadeuqate. Accordingly, an attempt was made to extend the steady-state predictive principles to "quasi-steady-state" modeling for the situtations encountered in the pilot sampling run. The development of this dynamic algorithm is described in the next section.

DYNAMIC ALGORITHM DEVELOPMENT

In this approach velocities for a given time period were calculated and a time step determined within the fixed period. Decay coefficient are incorporated for modeling non-conservative contaminants. Initial conditions for the system were determined by interpolating concentration at the nodes. After the system is "started" concentrations at a node for a given time step are calculated as the flow weighted concentration of all flows entering the node. Figure 12 shows the general routing procedure that is used for time steps within a given period and the equivalent distance that a contaminant wave front moves down the pipe. The horizontal axis shows the movement of a packet of water forward in time and the vertical axis shows the packet of water as it moves down the pipe. When the wave front intersects a given node it is reflected in the concentration at that node.

Figures 13 through 15 illustrate the application of the dynamic algorithm to a small hypothetical system shows with various initial contaminant concentrations at each node. For example, at node A, the initial concentration of a contaminant is given as 100. Figure 14 depicts the hydraulic system after the system has solved for the conditions that hold in period 1. Figure 15 illustrates the way the flow varies in the pipe with the time steps within period 1. The upper left corner is Period 1 at time step zero. Moving through the various time steps in a period allows one to see the routing of a given packet of water in the pipe. Time step 16 represents the last time step in period 1.

Figure 16 shows the flows and demands that exist in the pipe network during period two under a given set of demand conditions. Figure 17 shows the contaminant movement in Period 2. Figure 18 is intended to summarize the variations in quality that take place spatially in the system. The contour plots show the movement of the contaminants in the network over a period of time. This analysis illustrates the enormous amount of variability that can take place within a distribution system based on time, hydraulic demand and other time varying conditions.

SUMMARY AND CONCLUSIONS

There are many possibilities for water quality deterioration in drinking water distribution systmes. There is growing concern over the occurrence of coliform regrowth incidents and water borne disease outbreaks in the U.S. The Drinking Water Research Division of EPA has invested considerable research in examining various types of distribution system problems. These include microbiology, corrosion and infrastructure/system studies. One major area of investigation is the examination of variation of water quality and the effect of mixing in distribution systems and the ability to predict these variations. DWRD has initiated a cooperative agreement with the North Penn Water

Authority to study these variations in system water quality. Data from this study has verified the steady state modeling efforts. However, more effort is needed to establish the ability to predict dynamic variations in water quality.

Results of a short-term sampling run clearly show that significant differences in measured quality can be obtained in a multi-source distribution system, depending upon the time and location of sampling. This may have major implications for compliance monitoring strategies.

Initial steady-state modeling predicted that variations in water source and flow reversals would likely be seen at the Mainland sampling location. This pattern was in fact found. A more detailed analysis of the predictive capacity of steady-state modeling can at least predict zones in which such variations may be found.

The variation in TTHM at Keystone suggests that operational parameters are influencing the quality of the finished water. This variation was greater than expected, as it was assumed that the Keystone water would be relatively constant in quality over the period of the sampling run. Additional studies of Keystone water, using a shorter sampling interval and longer time spans, so that more diurnal cycles could be examined, will be made.

To date, it appears that most examination of dynamics of water in distribution systems has been restricted to hydraulics, with the general assumption that the quality of the product has been more or less constant. Perhaps the major conclusion that can be drawn from this effort is that examination of quality in water distribution systems must take into account spatial and temporal variations, and that assumptions relative to long and short-term constancy of behavior do not appear to be borne out. Ultimately these models will be very useful in designing future water quality surveys.

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TABLE 1. COLIFORM REGROWTH SITUATIONS INVESTIGATED BY U.S. EPA

Community	Popultion Estimate	Year
Muncie, IN	77,000	1980
Seymour, IN	15,000	1980
Bethlehem, PA	70,000	1981
Wilmette, IL	28,000	1981
Terre Haute, IN	61,000	1982
Springfield, IL	100,000	1982
Lexington, KY	204,000	1982
Florissant, MO	55,000	1984
Kennebunk, ME	3,000	1984
New Haven, CN	760,000	1984-1985
Minneapolis, Fairground, MN	250,000	1985
Monmouth, NJ	100,000	1985
Louisville, KY	298,000	1985
Iowa City, IO	50,000	1985
Fort Thomas, KY	16,000	1985

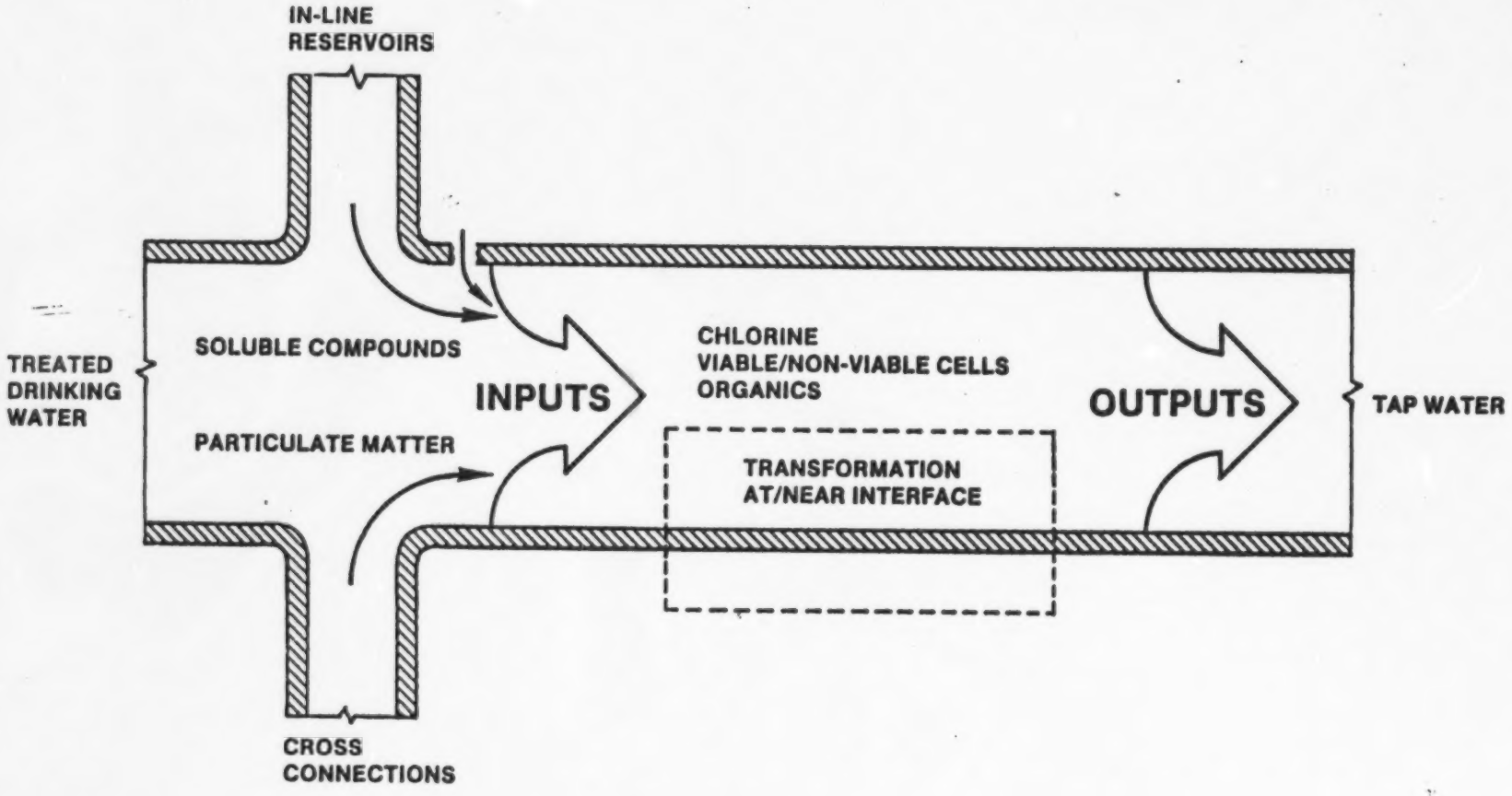


FIGURE 1. WATER DISTRIBUTION PIPE

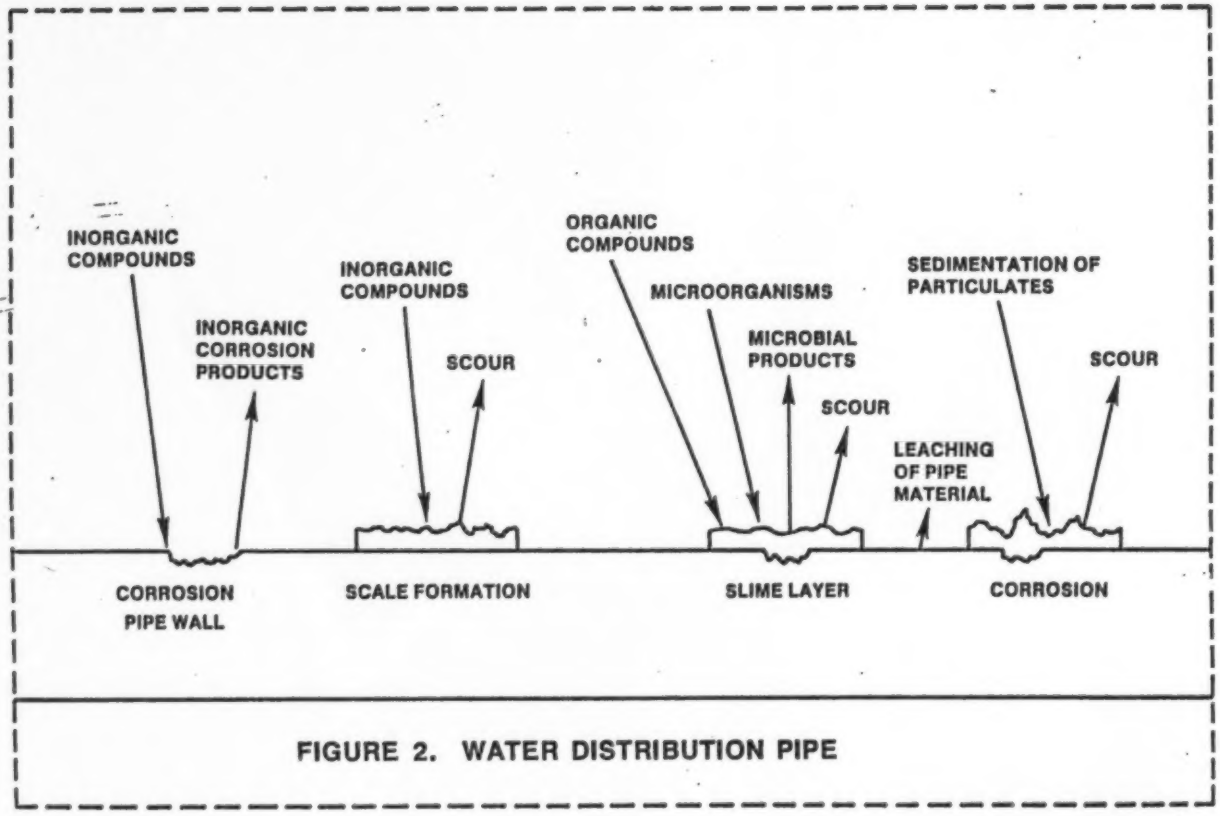


FIGURE 2. WATER DISTRIBUTION PIPE

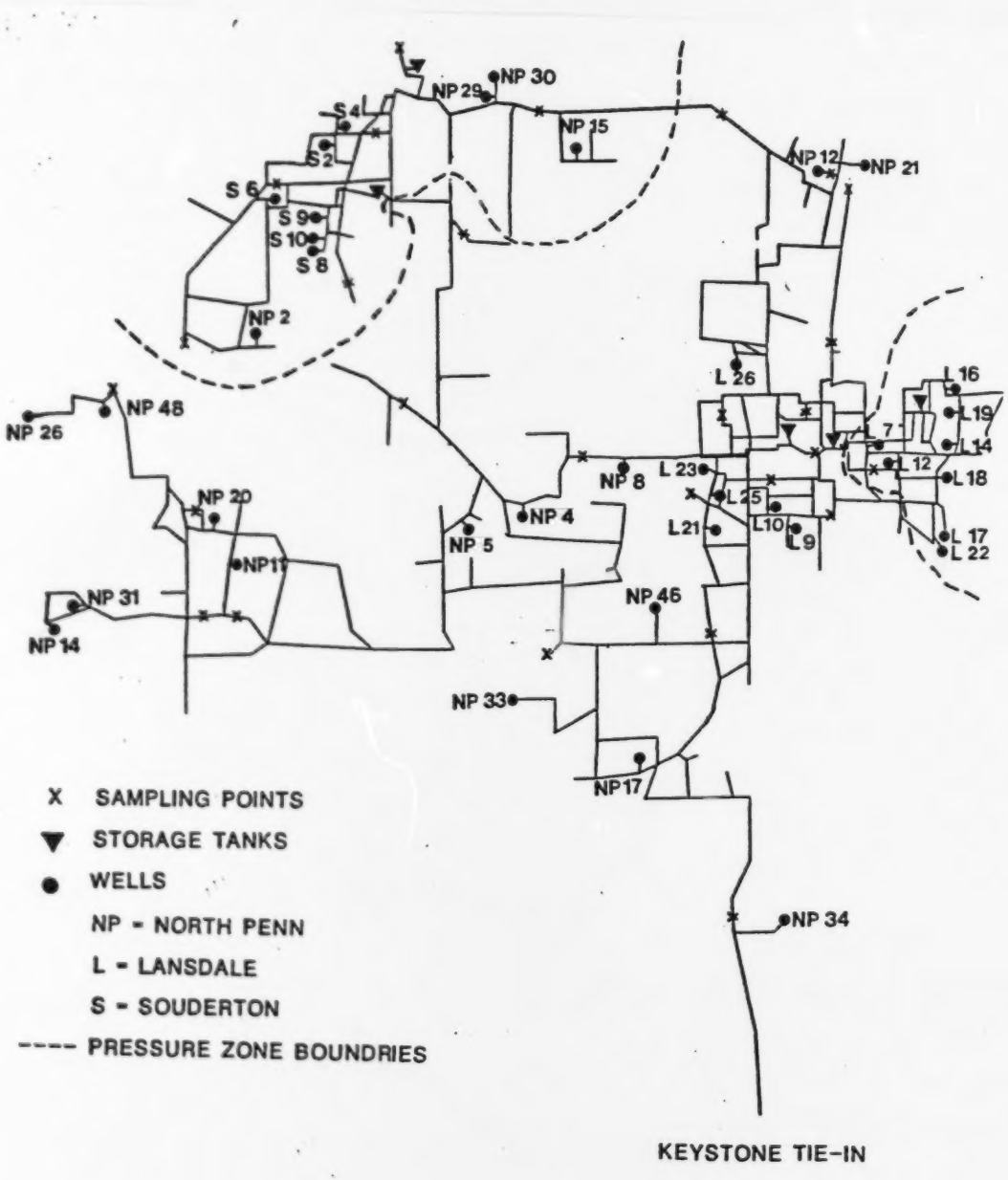


FIGURE 3. NORTH PENN WATER AUTHORITY WATER DISTRIBUTION SYSTEM

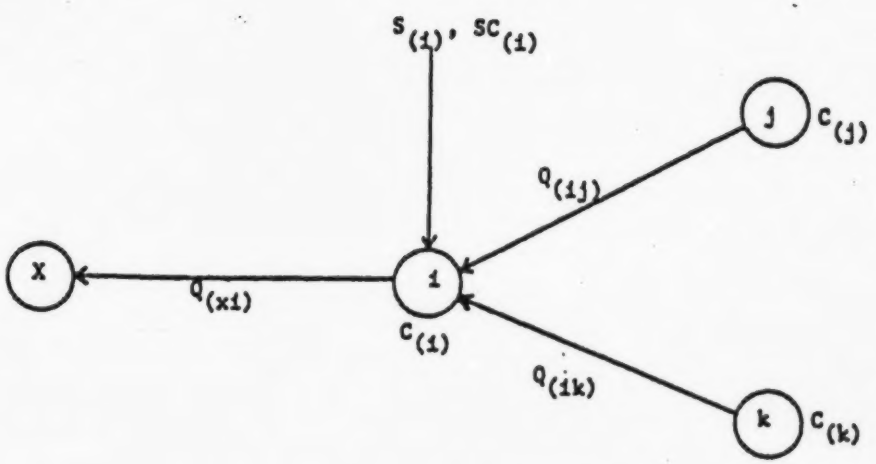


FIGURE 4. CONCENTRATION EXAMPLE

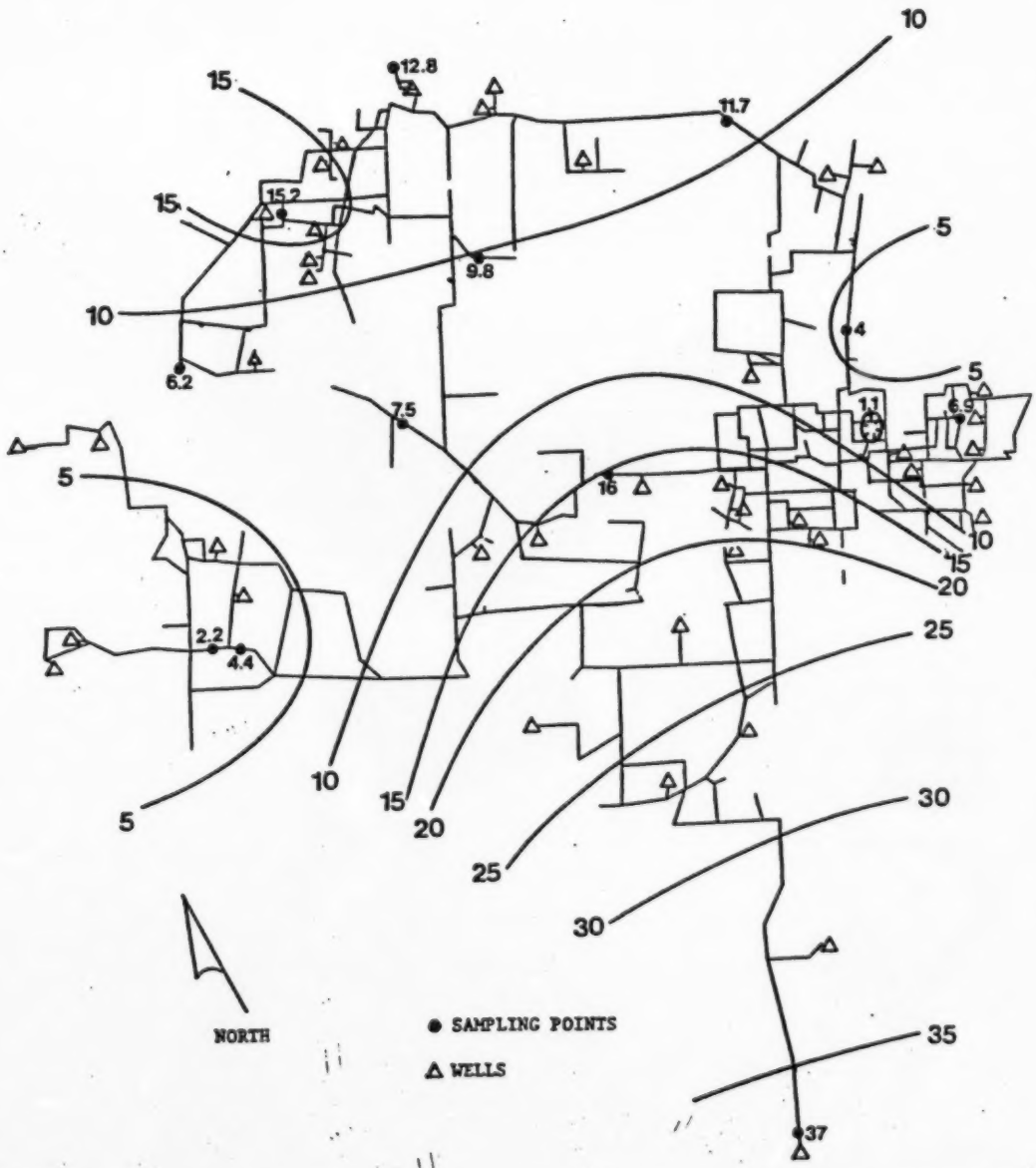


FIGURE 5. DAILY TTHM CONCENTRATION CONTOURS FOR 4-16-84 (UG/L)

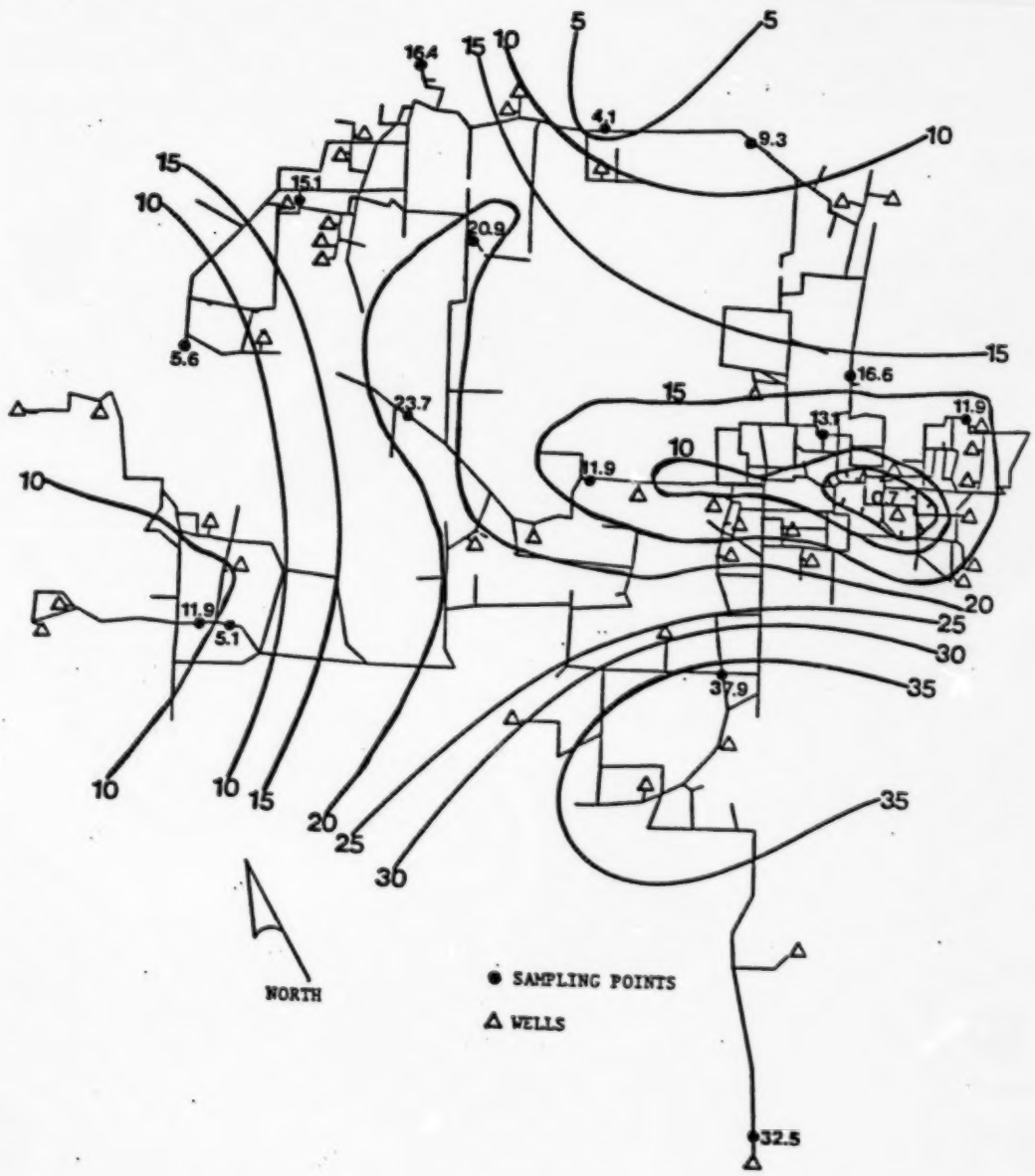


FIGURE 6. DAILY TTHM CONCENTRATION CONTOURS FOR 4-16-85 (UG/L)

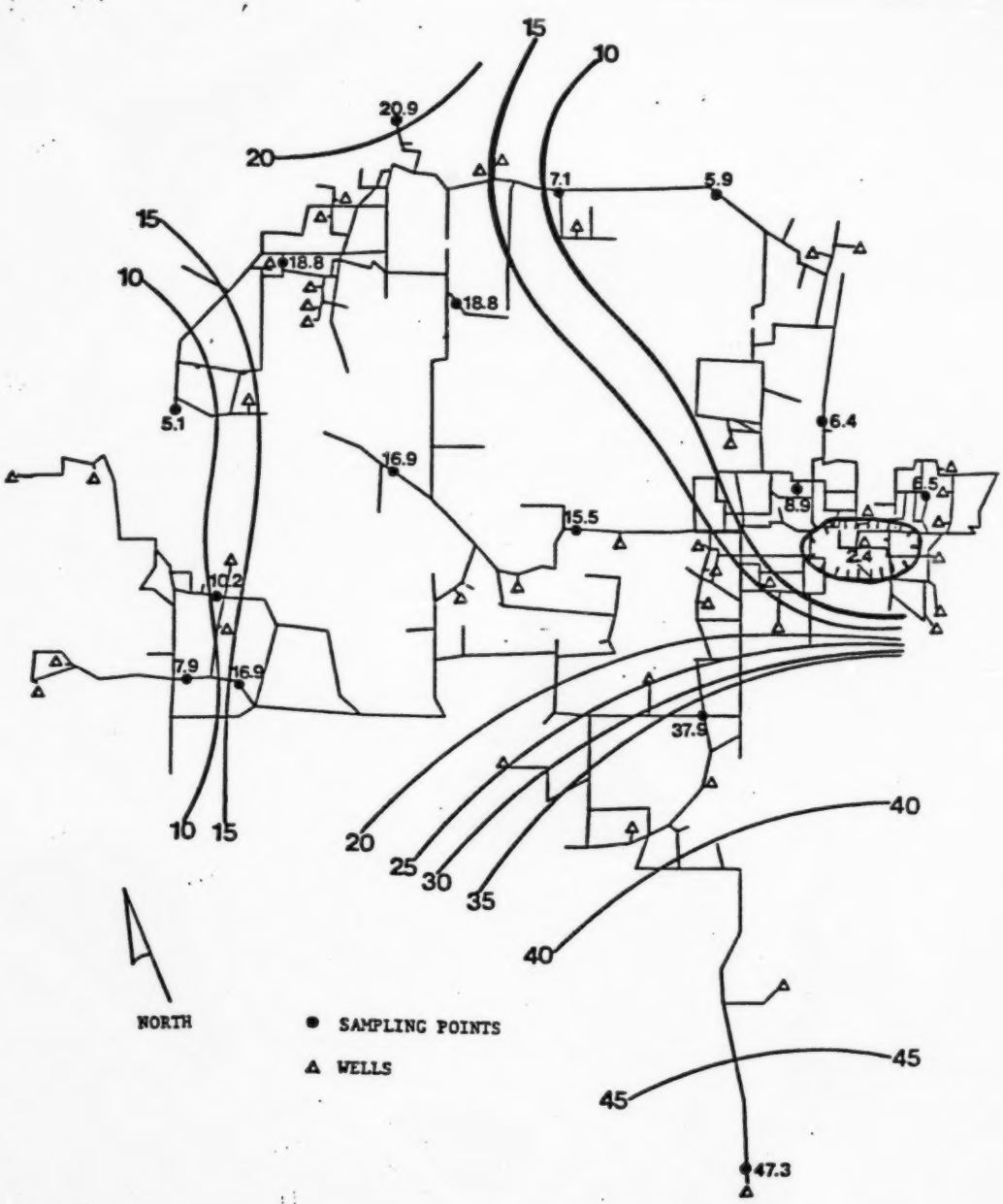


FIGURE 7. AVERAGE TTHM CONCENTRATION CONTOURS (UG/L)

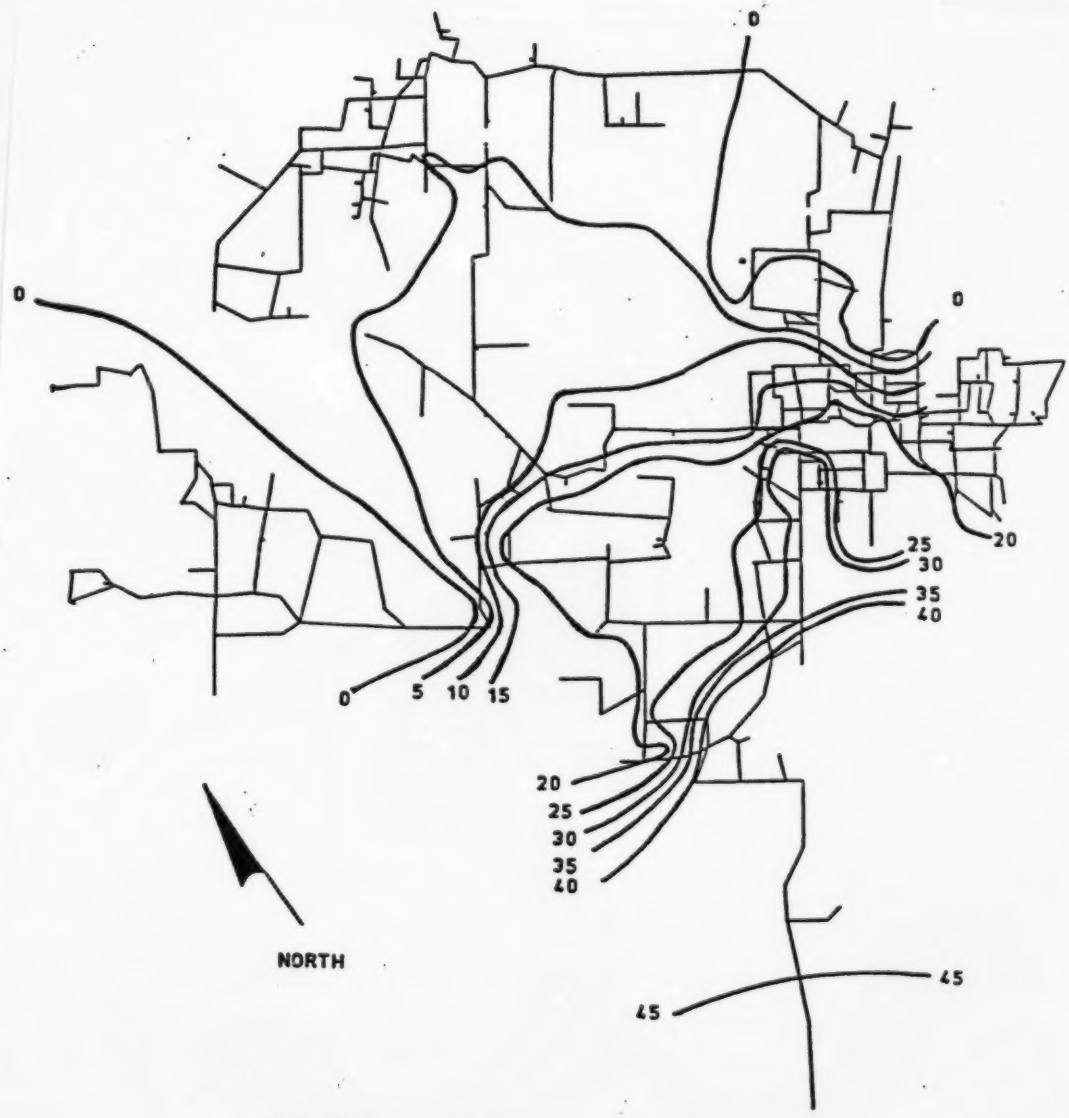


FIGURE 8. MODEL PREDICTIONS TTHM'S

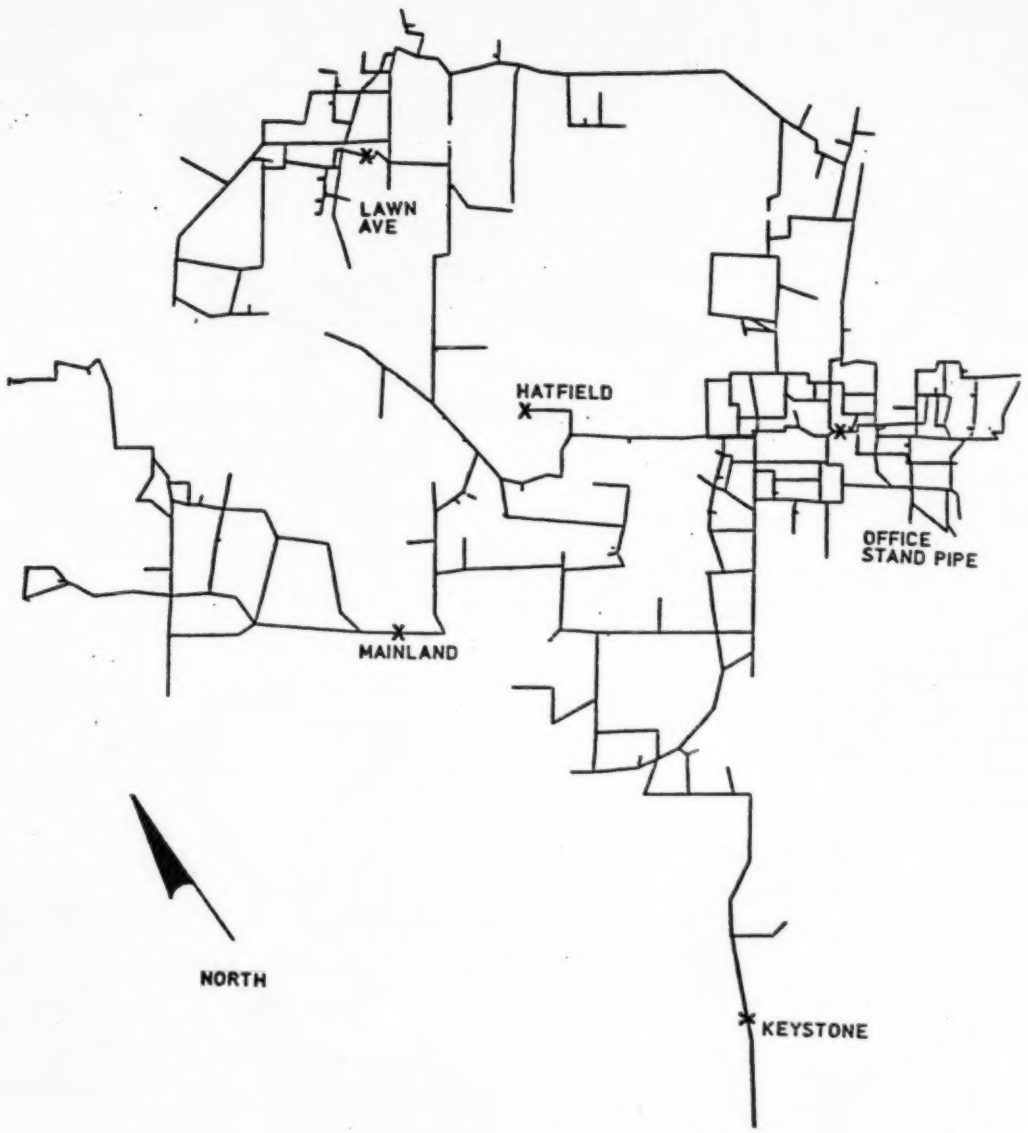


FIGURE 9. SAMPLING POINTS FOR FIELD STUDY

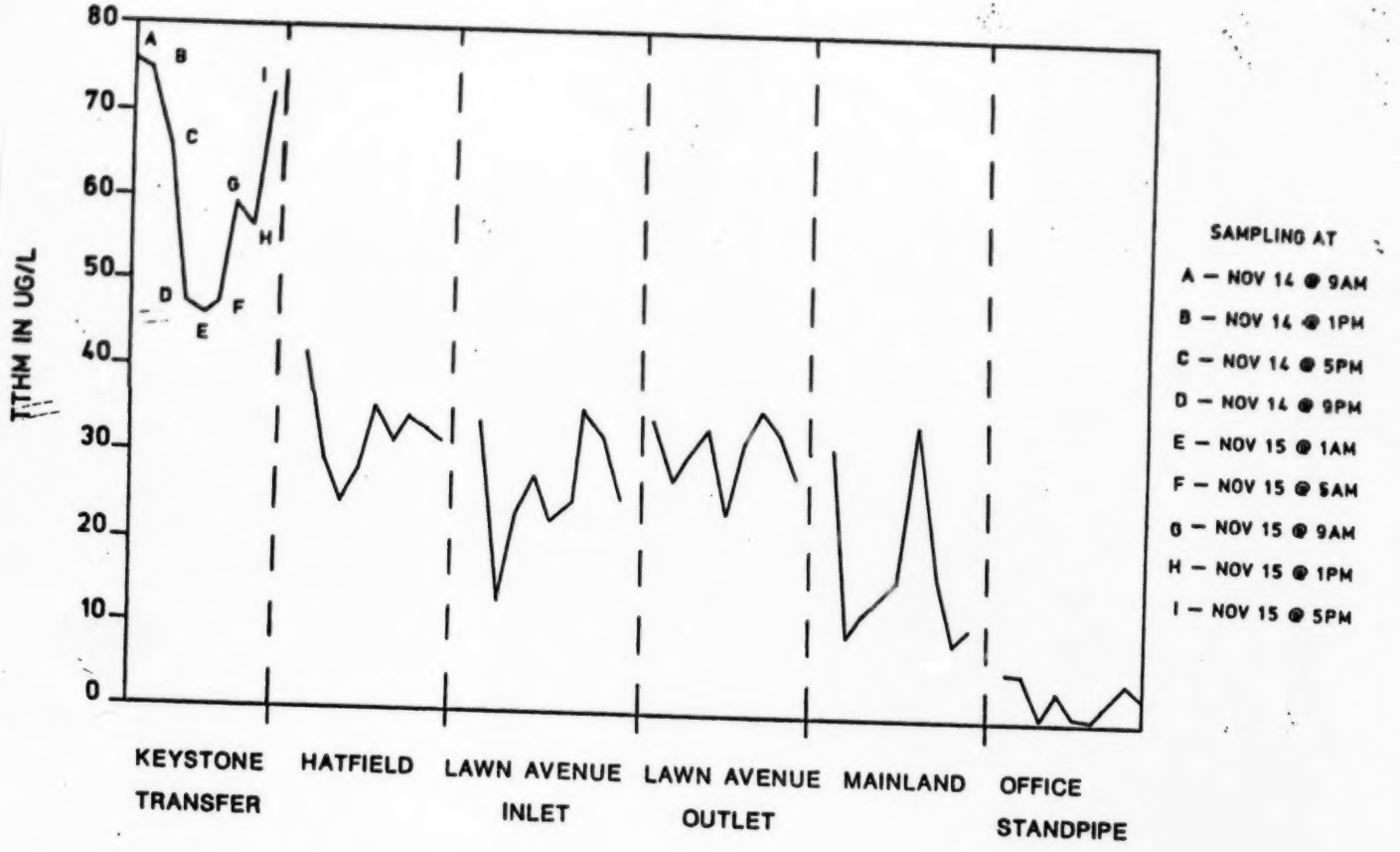


FIGURE 10. SAMPLING RESULTS FROM SIX SAMPLING STATIONS IN NORTH PENN WATER AUTHORITY

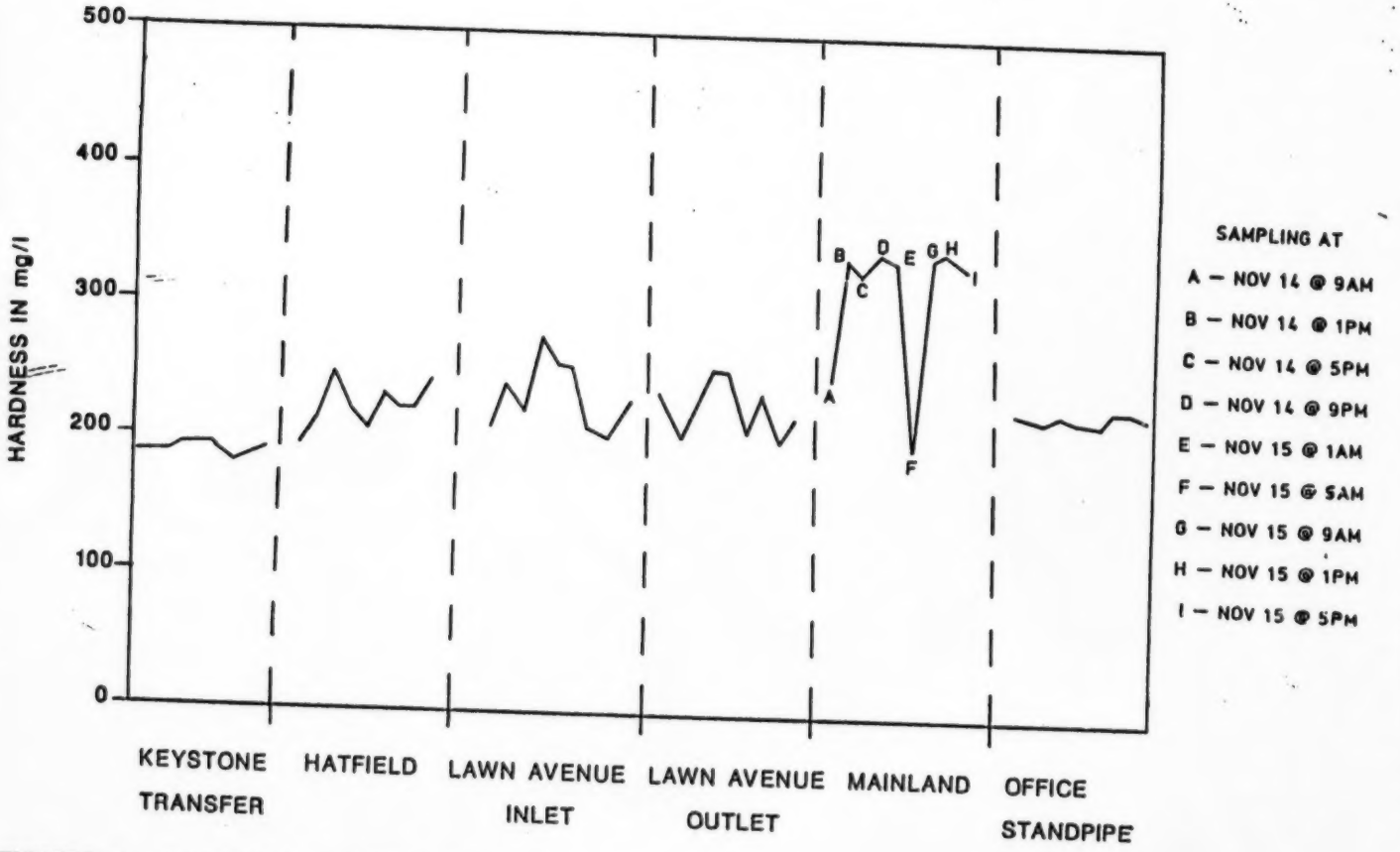
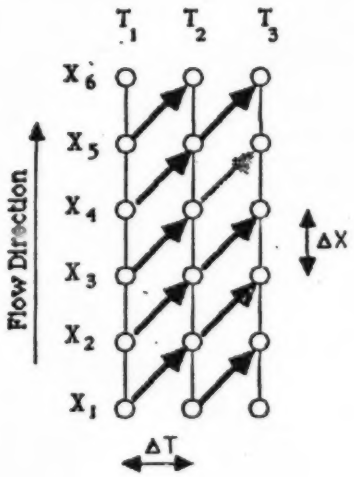


FIGURE 11. SAMPLING RESULTS FROM SIX SAMPLING STATIONS IN NORTH PENN WATER AUTHORITY



General equation:

$C_{x+1,t+1} = C_{x,t}$

where $C_{x,t}$ = concentration at sub node x at time step t

Example (see shaded arrow):

$C_{5,3} = C_{4,2}$

FIGURE 12. GENERAL ROUTING PROCEDURE FOR DYNAMIC ALGORITHM

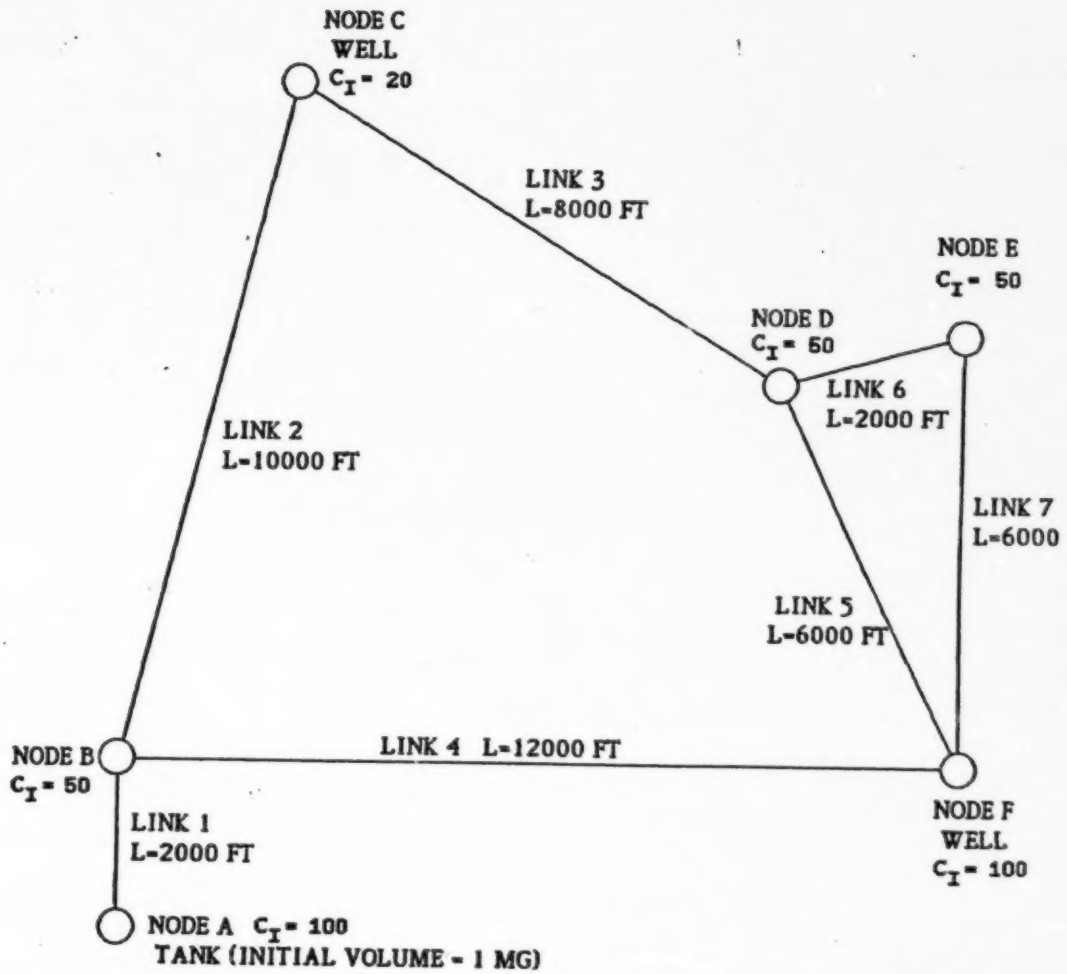


FIGURE 13. SAMPLE NETWORK

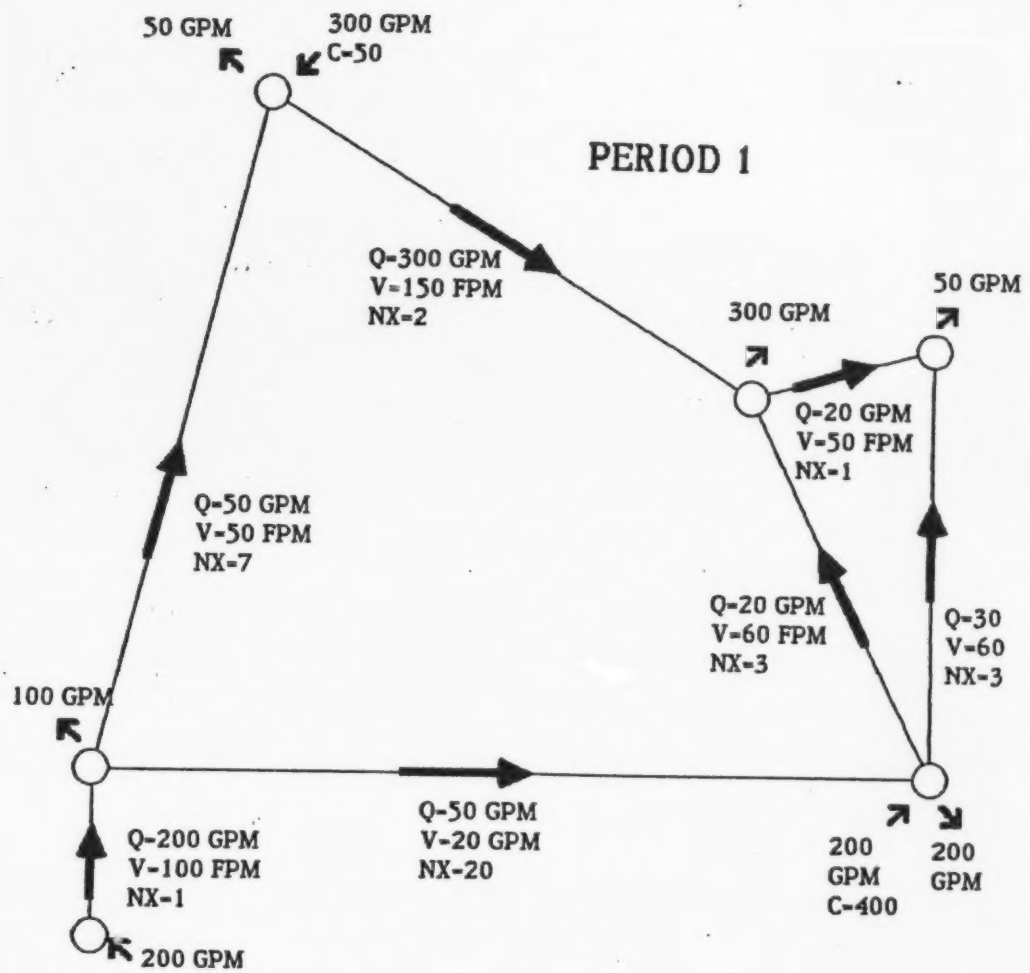


FIGURE 14. SAMPLE NETWORK WITH HYDRAULIC SOLUTION FOR PERIOD 1

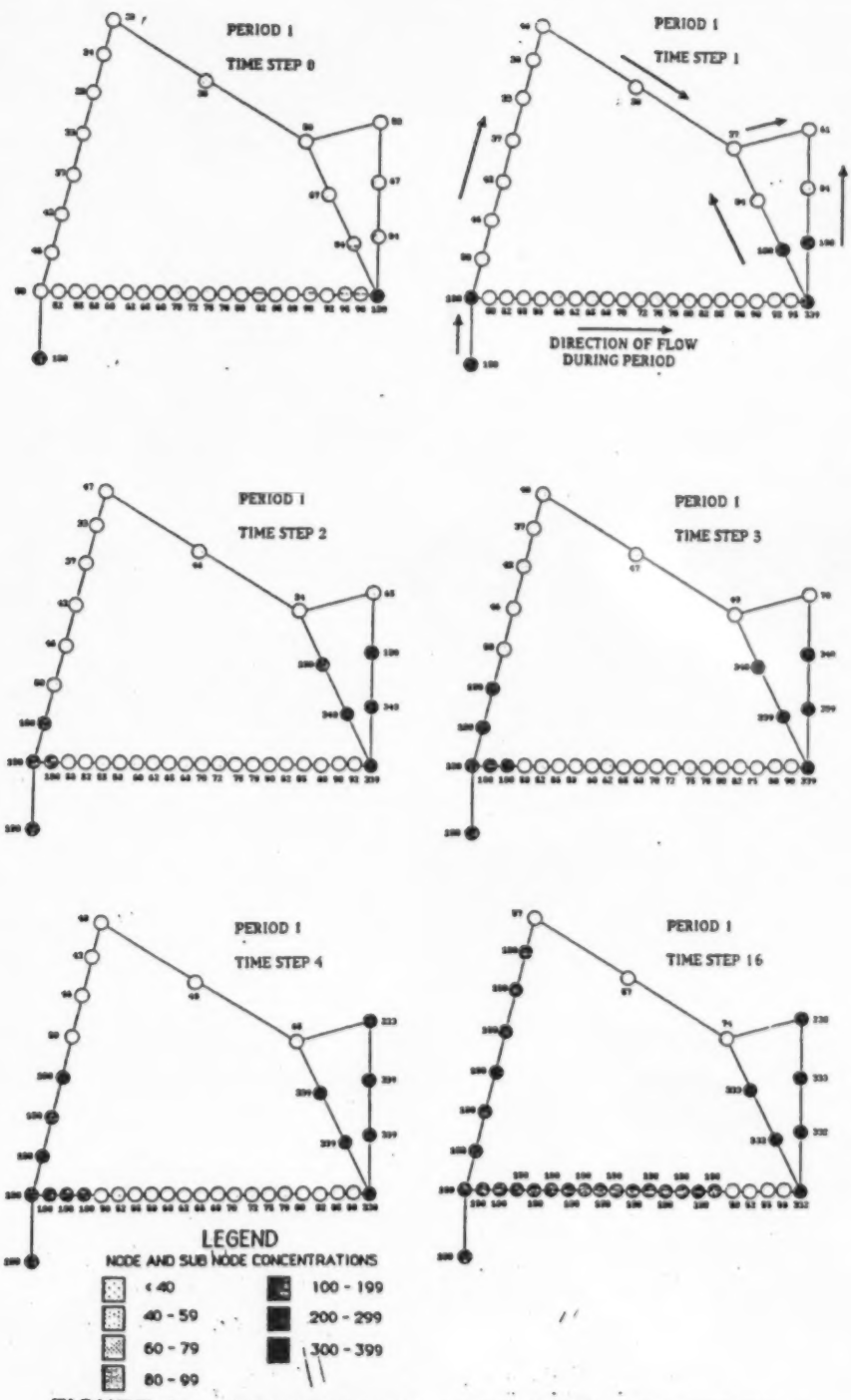


FIGURE 15. SOLUTION TO ALGORITHM FOR PERIOD 1

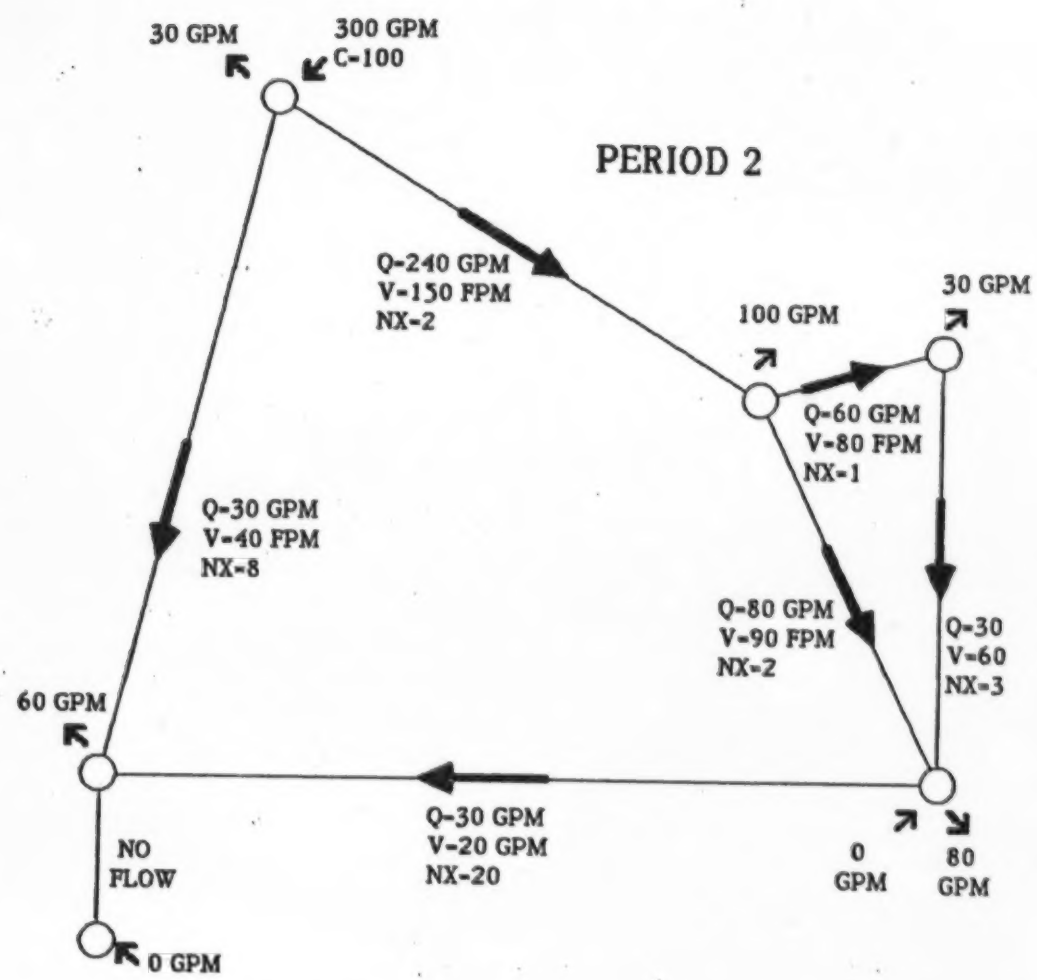


FIGURE 16. SAMPLE NETWORK WITH HYDRAULIC SOLUTION FOR PERIOD 2 AND INITIAL CONDITIONS FROM PERIOD 1

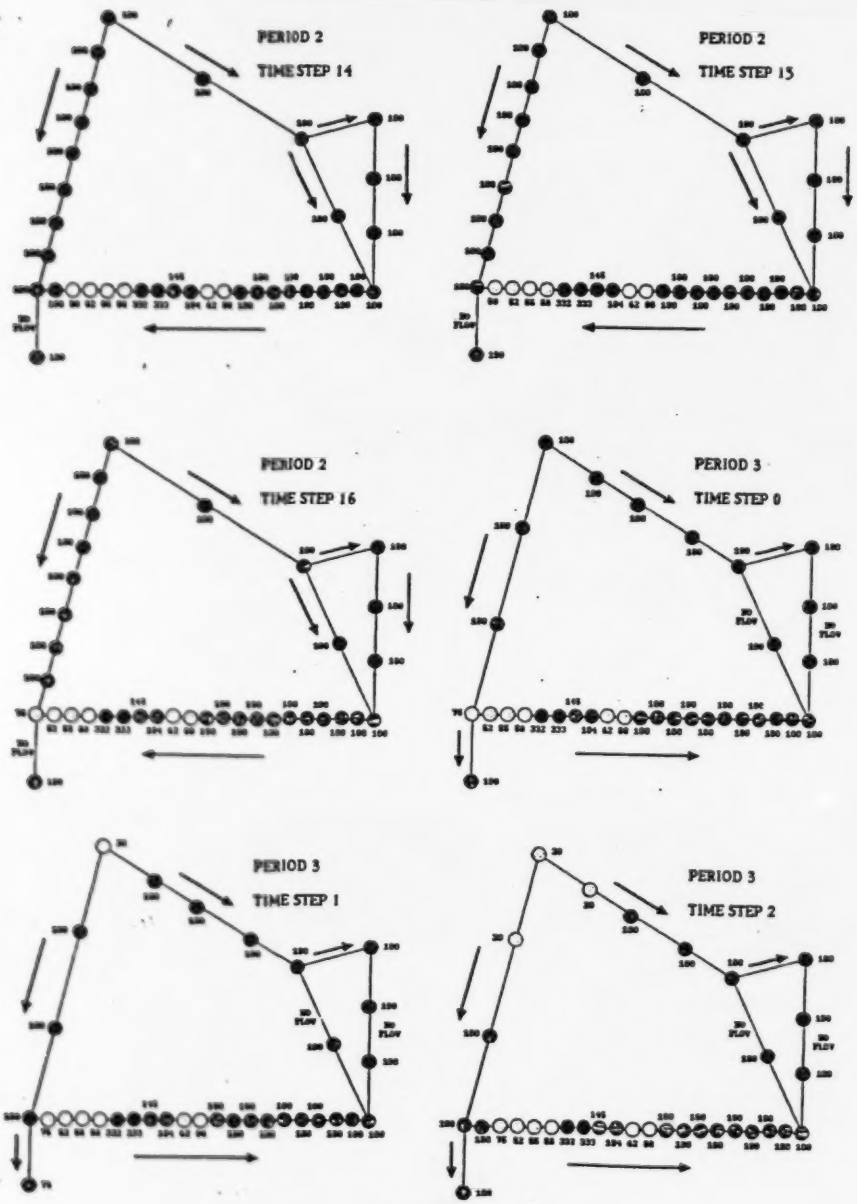


FIGURE 17. SOLUTION TO ALGORITHM FOR PERIOD 2

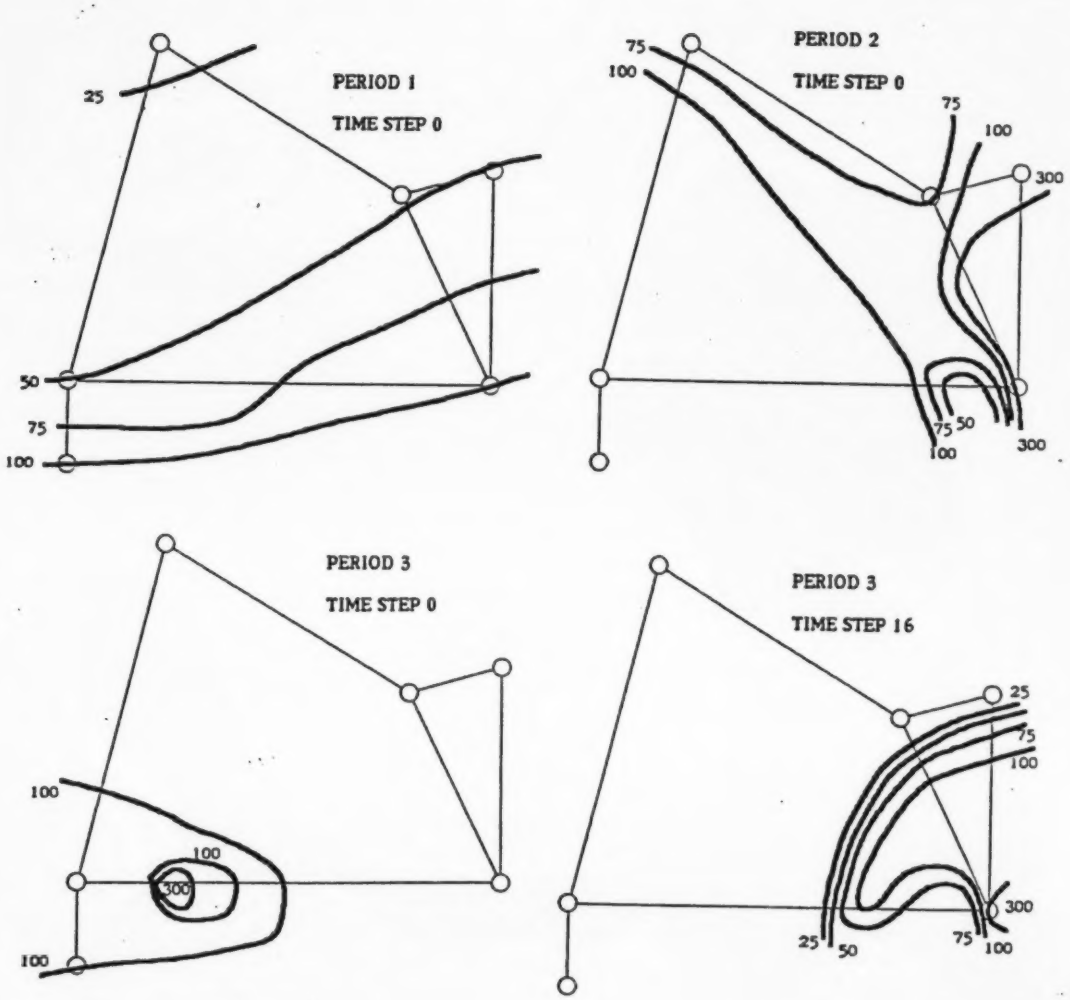


FIGURE 18. SIMULATED CONTAMINANT MOVEMENT UNDER DYNAMIC CONDITIONS